The β–ν Correlation in Laser-Trapped ^{21}Na and the Standard Model

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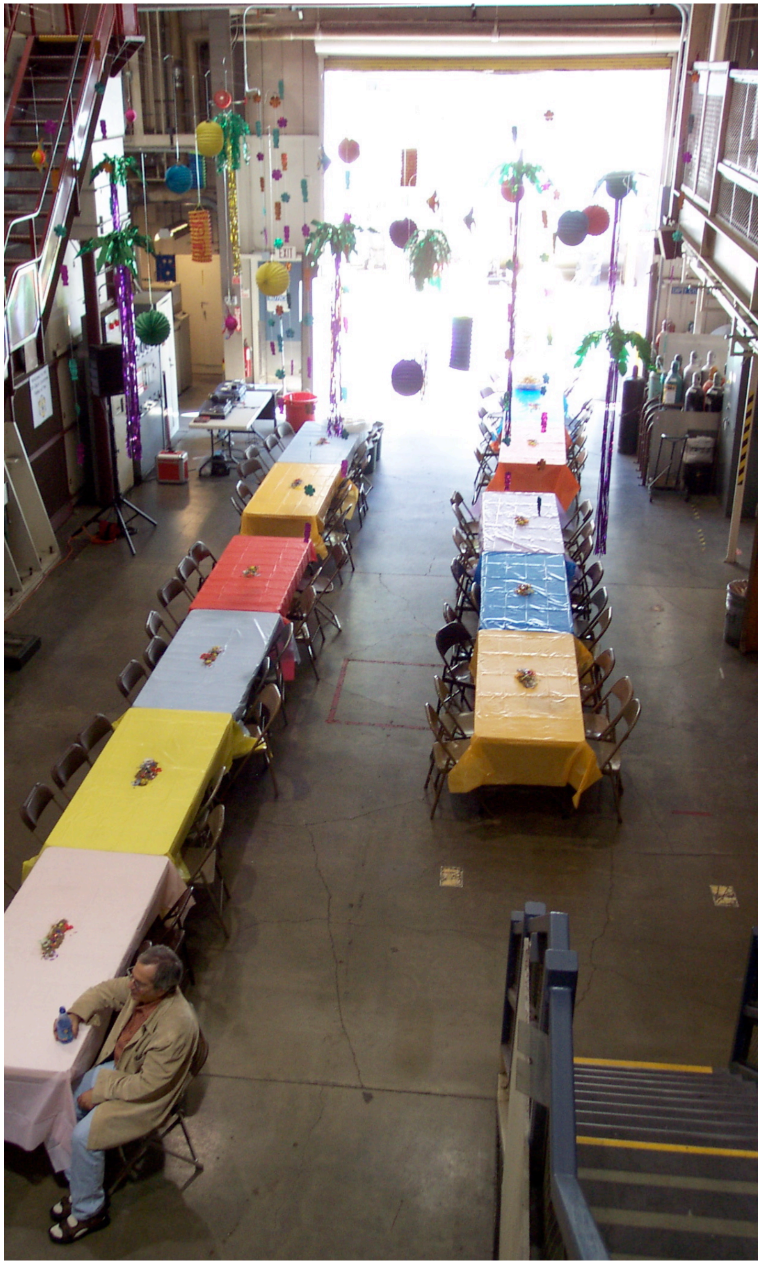

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The electroweak Lagrangian

$$
\begin{aligned}
\mathscr{L}_F &= \sum_i \bar{\psi}_i \left(i \not{\partial} - m_i - \frac{g m_i H}{2 M_W} \right) \psi_i \\
&- \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu \left(1 - \gamma^5\right) \left(T^+ W_\mu^+ + T^- W_\mu^-\right) \psi_i \\
&- e \sum_i q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu \\
&- \frac{g}{2\cos\theta_W} \sum_i \bar{\psi}_i \gamma^\mu \left(g_V^i - g_A^i \gamma^5\right) \psi_i Z_\mu
\end{aligned}
$$

$$\mathscr{L}_F = \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu \left(1 - \gamma^5\right) \left(T^+ W_\mu^+ + T^- W_\mu^-\right) \psi_i$$

Fermions come in doublets

$$\psi_i = \left(\begin{array}{c} \nu_i \\ \ell_i^- \end{array} \right) \qquad \left(\begin{array}{c} u_i \\ d_i' \end{array} \right)$$

$$d_i' = \sum_i V_{ij} d_j$$

Where quark mixing is a unitary transform like this:

$$V_{ij} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Which can be written as:

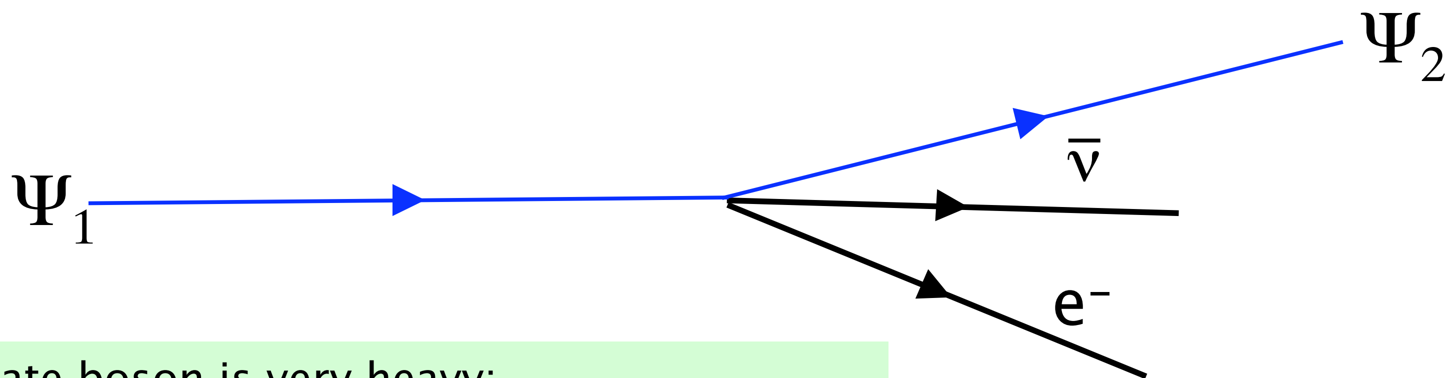
$$V_{ij} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\left(\rho - i\eta\right) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix}$$

$$+O\left(\lambda^4\right)$$

So is this all there is?

$$\mathscr{L}_F = \frac{g}{2\sqrt{2}} \sum_i \bar{\psi}_i \gamma^\mu \left(1 - \gamma^5\right) \left(T^+ W_\mu^+ + T^- W_\mu^-\right) \psi_i$$

Nuclear beta decay four fermion interaction



Intermediate boson is very heavy:
Point-like interaction of the four fermions' currents

Isospin quantum numbers in the nucleus

$$
\begin{aligned}
H_{\text{int}} \quad = \quad & \left(\bar{\psi}_2 \psi_1\right)\left(C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu\right) \\
& + \left(\bar{\psi}_2 \gamma_\mu \psi_1\right)\left(C_V \bar{\psi}_e \gamma^\mu \psi_\nu + C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu\right) \\
& + 1/2 \left(\bar{\psi}_2 \sigma_{\lambda\mu} \psi_1\right)\left(C_T \bar{\psi}_e \sigma^{\lambda\mu} \psi_\nu + C'_T \bar{\psi}_e \sigma^{\lambda\mu} \gamma_5 \psi_\nu\right) \\
& - \left(\bar{\psi}_2 \gamma_\mu \gamma_5 \psi_1\right)\left(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma^\mu \psi_\nu\right) \\
& + \left(\bar{\psi}_2 \gamma_5 \psi_1\right)\left(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu\right)
\end{aligned}
$$

19 free parameters for complex C_i's

Calculate the decay rate

$$
\begin{aligned}
\frac{d^4W\left(\mathbf{p}_e,\mathbf{p}_\nu,\mathbf{I}\right)}{d\Omega_e d\Omega_\nu} \quad = \quad & \xi\left\{1 + a_{\beta\nu}\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu} + b_{\mathrm{Fierz}}\frac{m_e}{E_e} + \frac{\langle\mathbf{I}\rangle}{I}\cdot\left[A_\beta\frac{\mathbf{p}_e}{E_e} + B_\nu\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\right. \\
& \left. + c_{\mathrm{align}}\left[\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{3E_eE_\nu} - \frac{\left(\mathbf{p}_e\cdot\hat{i}\right)\left(\mathbf{p}_\nu\cdot\hat{i}\right)}{E_eE_\nu}\right]\left[\frac{I\left(I+1\right) - 3\left\langle\left(\mathbf{I}\cdot\hat{i}\right)^2\right\rangle}{I\left(2I+1\right)}\right]\right\}
\end{aligned}
$$

+ terms with β polarization

Jackson, Treiman, Wyld, *Phys. Rev.* **106**, p. 517 (1957)

Correlation coefficients in terms of four-fermion coupling constants

Jackson, Treiman and Wyld, *Phys. Rev.* **106**, 517 (1957).

$$\xi=|M_F|^2(|C_S|^2+|C_V|^2+|C_S'|^2+|C_V'|^2)+|M_{GT}|^2(|C_T|^2+|C_A|^2+|C_T'|^2+|C_A'|^2),$$

$$a\xi=|M_F|^2(-|C_S|^2+|C_V|^2-|C_S'|^2+|C_V'|^2)+\frac{|M_{GT}|^2}{3}(|C_T|^2-|C_A|^2+|C_T'|^2-|C_A'|^2),$$

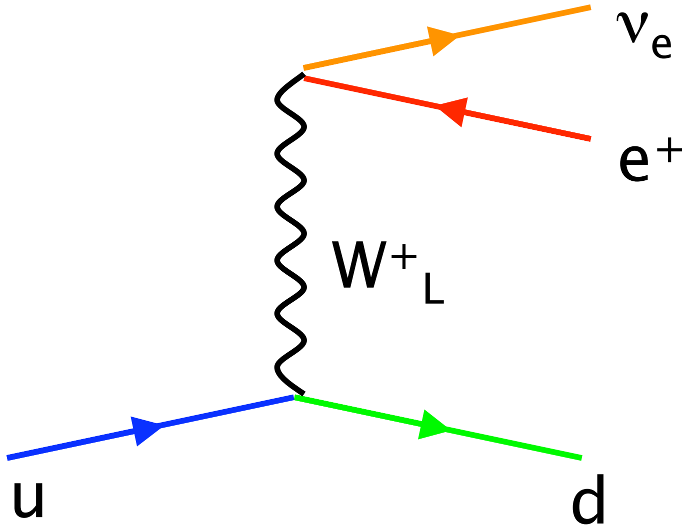
$$b\xi=\pm 2\,\mathrm{Re}[|M_F|^2(C_SC_V^*+C_S'C_V'^*)+|M_{GT}|^2(C_TC_A^*+C_T'C_A'^*)],$$

Helicity Projection Formalism

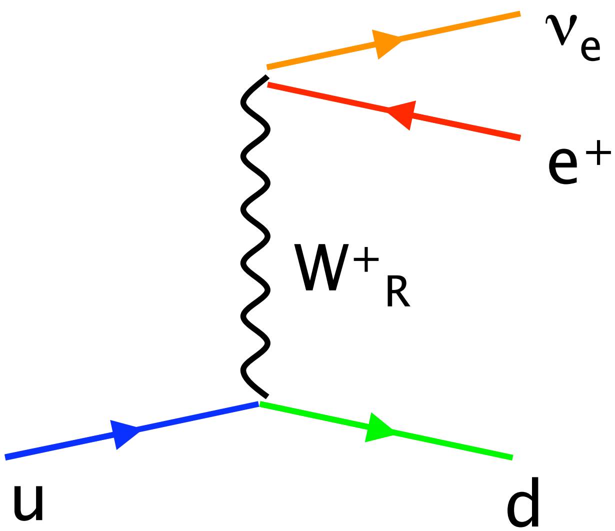
P. Herczeg, *Prog. Nucl. Part. Phys.* **46**, 213 (2001).
Severijns, Beck and Naviliat-Cuncic, *Rev. Mod. Phys.* **78**, 991 (2006).

Relate C_i's to g_S a_{LR} A_{LR}

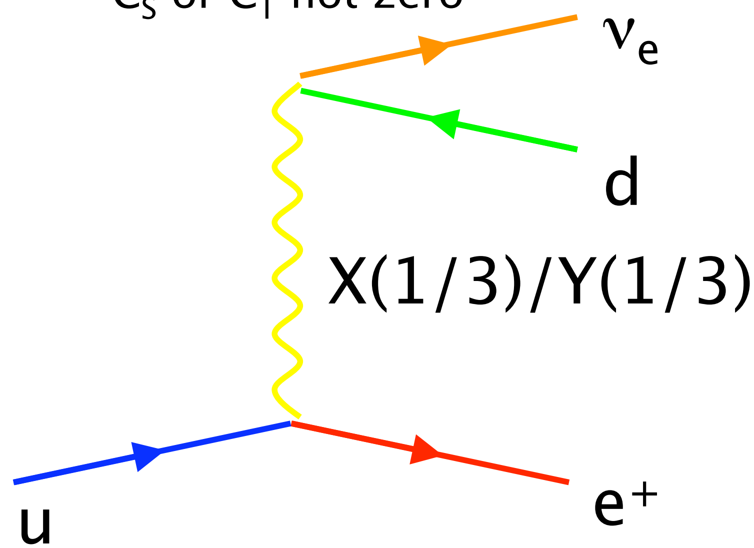
Michel parameter related formalism, more coefficients (flavor dependence)…



Right handed W boson -- C' s not zero

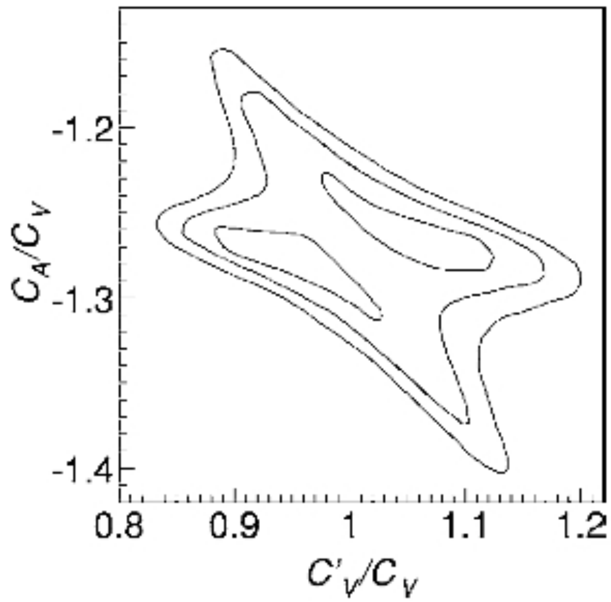


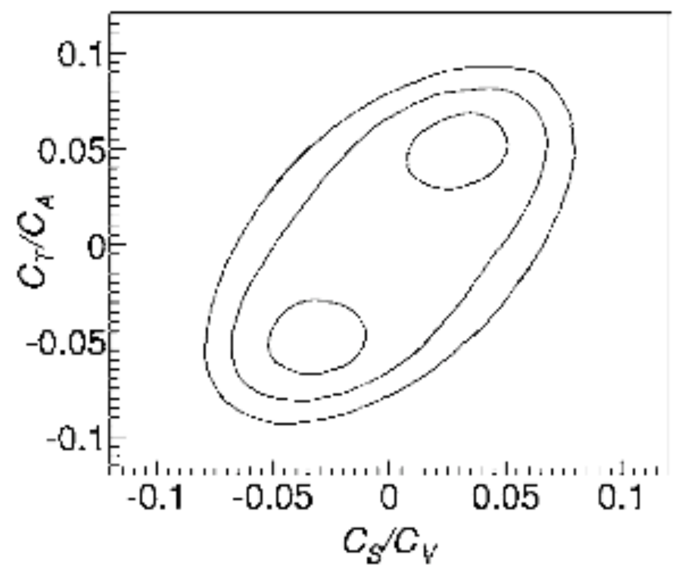
Scalar or tensor leptoquark
C_S or C_T not zero



Limits on Non-Standard Model Couplings

N. Severijns, M. Beck, and O. Naviliat-Cuncic, Rev. Mod. Phys. **78**, 991 (2006)





Two possible exclusion plots
Non-StdMod couplings can be ~10% of allowed
Best fit with neutron data suggests new physics

Scalar, tensor couplings can be induced by leptoquarks, left-right symmetry
Supersymmetry, charged Higgs exchange.
P. Herczeg, Prog. Part. Nucl. Phys. **46**, 413 (2001).

- Available model space to test is very large -- many degrees of freedom
- High energy tests do not span the model space
- Current limits on non-Standard couplings are generally not stringent

Beta neutrino correlation searches for Scalar, Tensor couplings

$$a_{\beta\nu} = \frac{|M_F|^2\left(|C_V|^2+\left|C_V'\right|^2-|C_S|^2-\left|C_S'\right|^2\right)-\frac{1}{3}|M_{GT}|^2\left(|C_A|^2+\left|C_A'\right|^2-|C_T|^2-\left|C_T'\right|^2\right)}{|M_F|^2\left(|C_V|^2+\left|C_V'\right|^2+|C_S|^2+\left|C_S'\right|^2\right)+|M_{GT}|^2\left(|C_A|^2+\left|C_A'\right|^2+|C_T|^2+\left|C_T'\right|^2\right)}$$

$$M_F = \langle 1 \rangle = \langle \Psi_f \,|\tau_\pm|\, \Psi_i \rangle$$

$$M_{GT} = \langle \sigma \rangle = \langle \Psi_f \,|\vec{\sigma}\tau_\pm|\, \Psi_i \rangle$$

Calculate a in the Standard Model as:

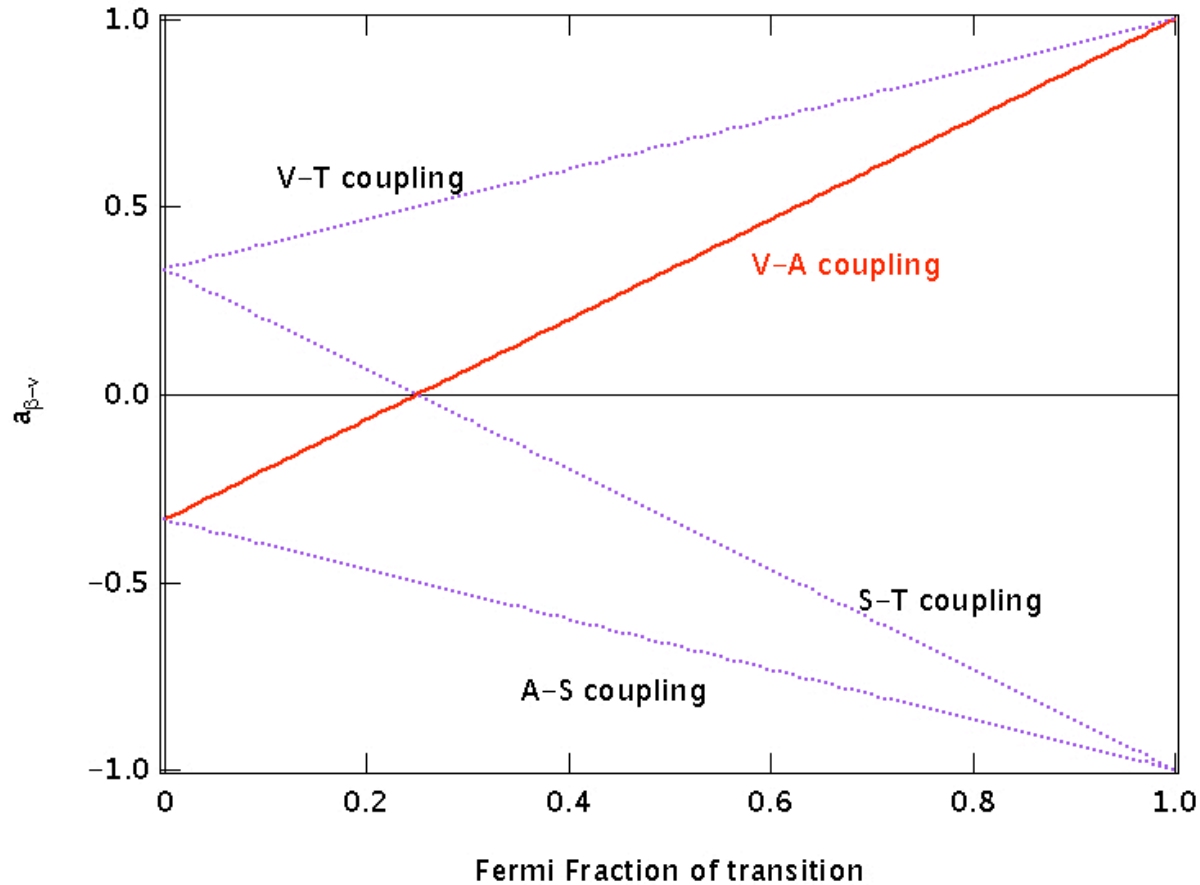
$$a_{\beta\nu} = \frac{1-\lambda^2/3}{1+\lambda^2}$$

Where λ is the ratio of axial vector to vector (G-T to Fermi) in the transition

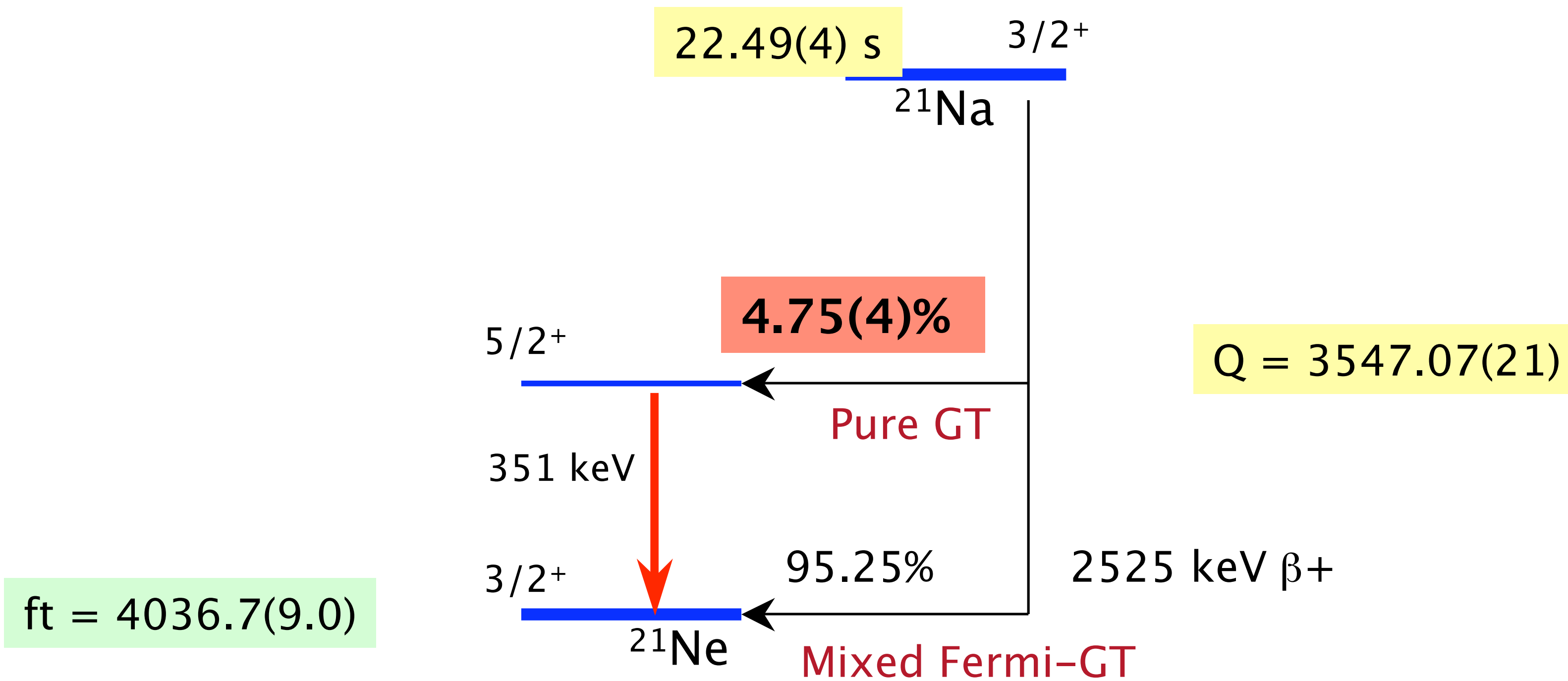
$$\lambda = \frac{C_A\langle\sigma\rangle}{C_V\langle 1\rangle}$$

Beta Neutrino Correlation Measurements

$a_{\beta\nu}$ plotted as a function of the Fermi fraction of the transition



Decay scheme of ^{21}Na

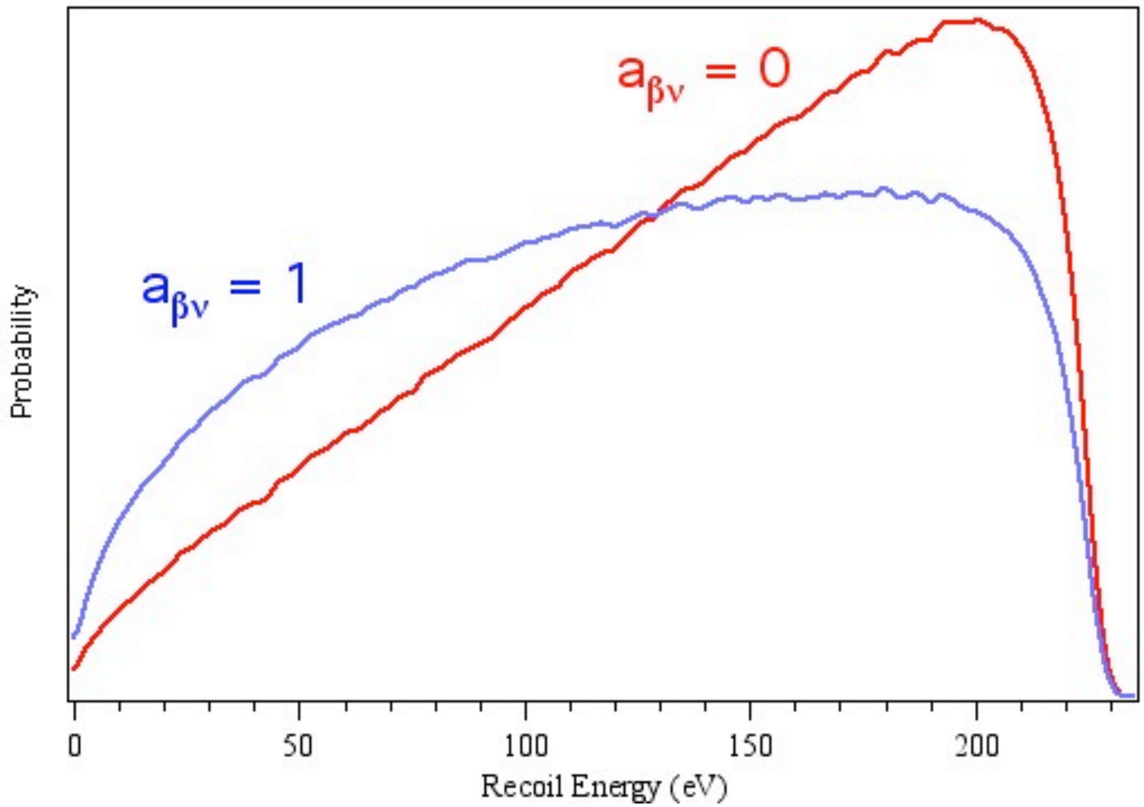


^{21}Na $3/2^+ \rightarrow$ ^{21}Ne $3/2^+$:

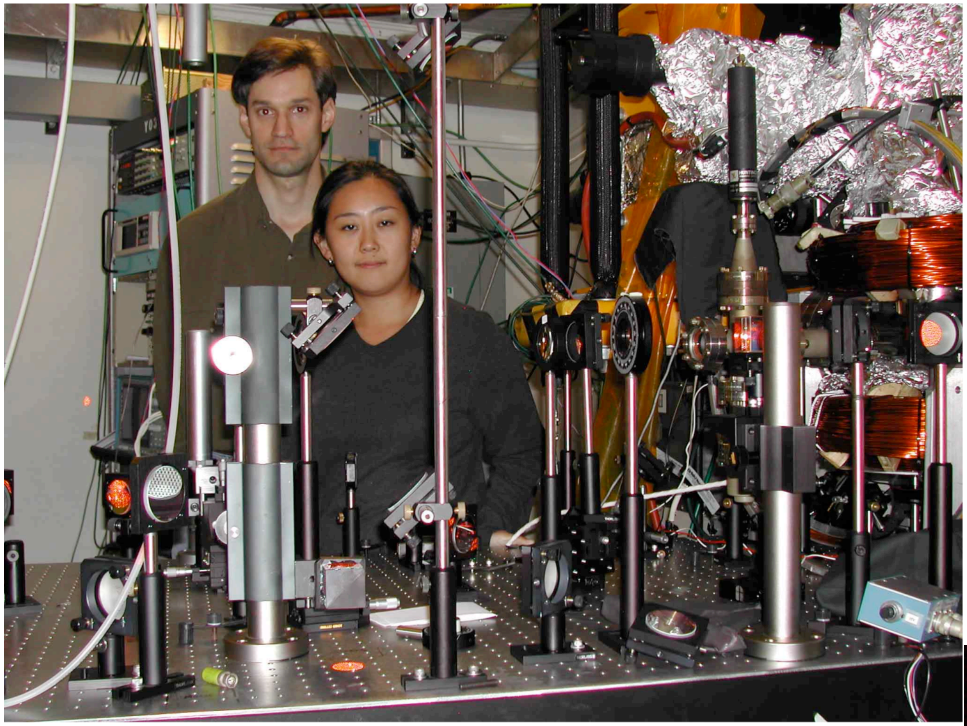
$\langle 1 \rangle = 1$ Fermi matrix element -- isodoublet mirror transition

$C_A \langle \sigma \rangle = 0.703(3)$ Gamow -Teller matrix element (calculated)

Recoil energy spectrum for ^{21}Na



Apparatus

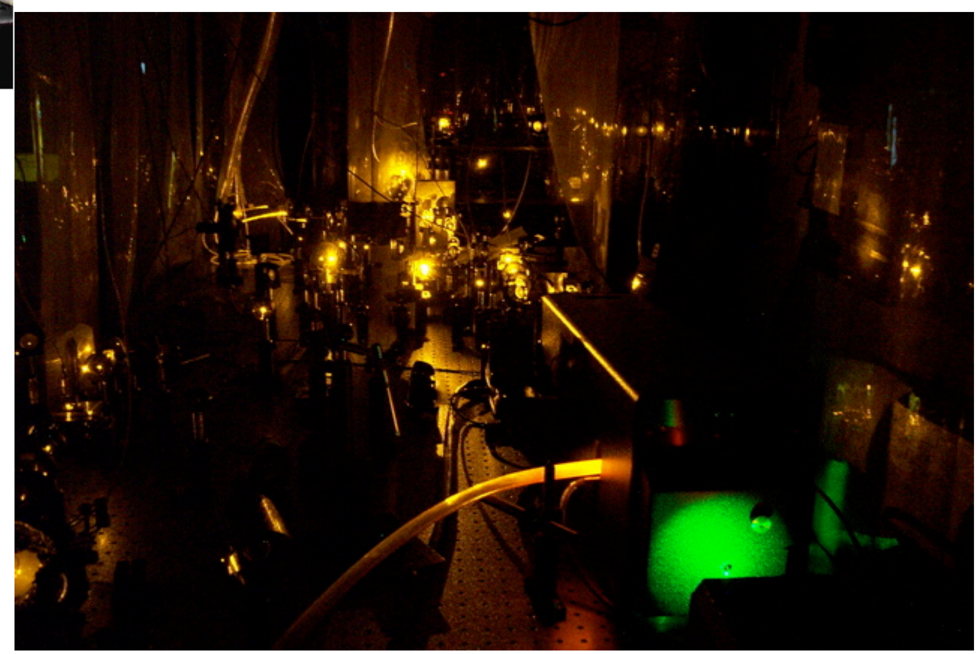


Neutral atom trap for ^{21}Na

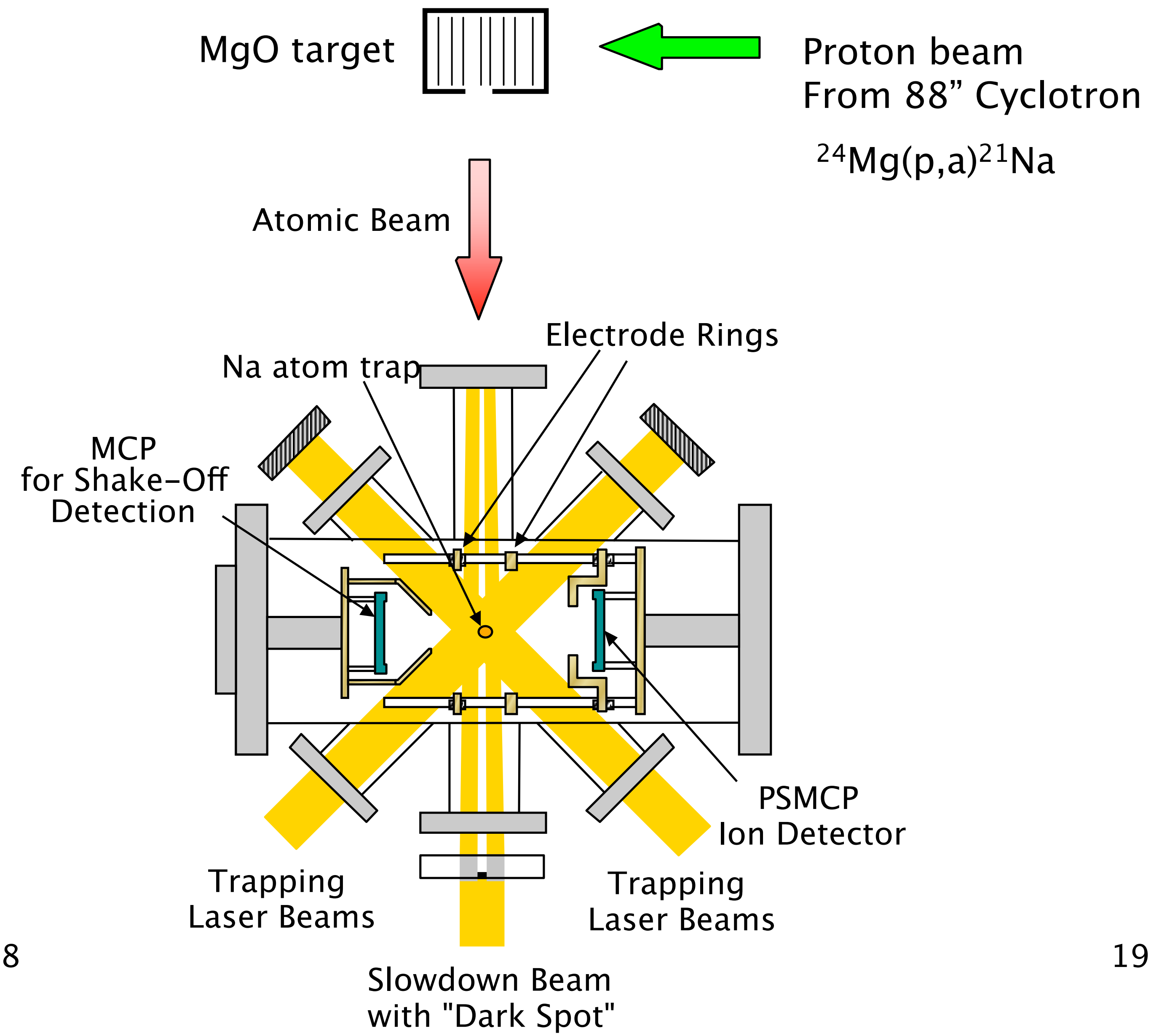
Measure total energy/momentum spectrum of recoil nuclei

Time-of-flight momentum spectrometer

T=0 start provided by shake-off electrons
High efficiency, run with low trap density

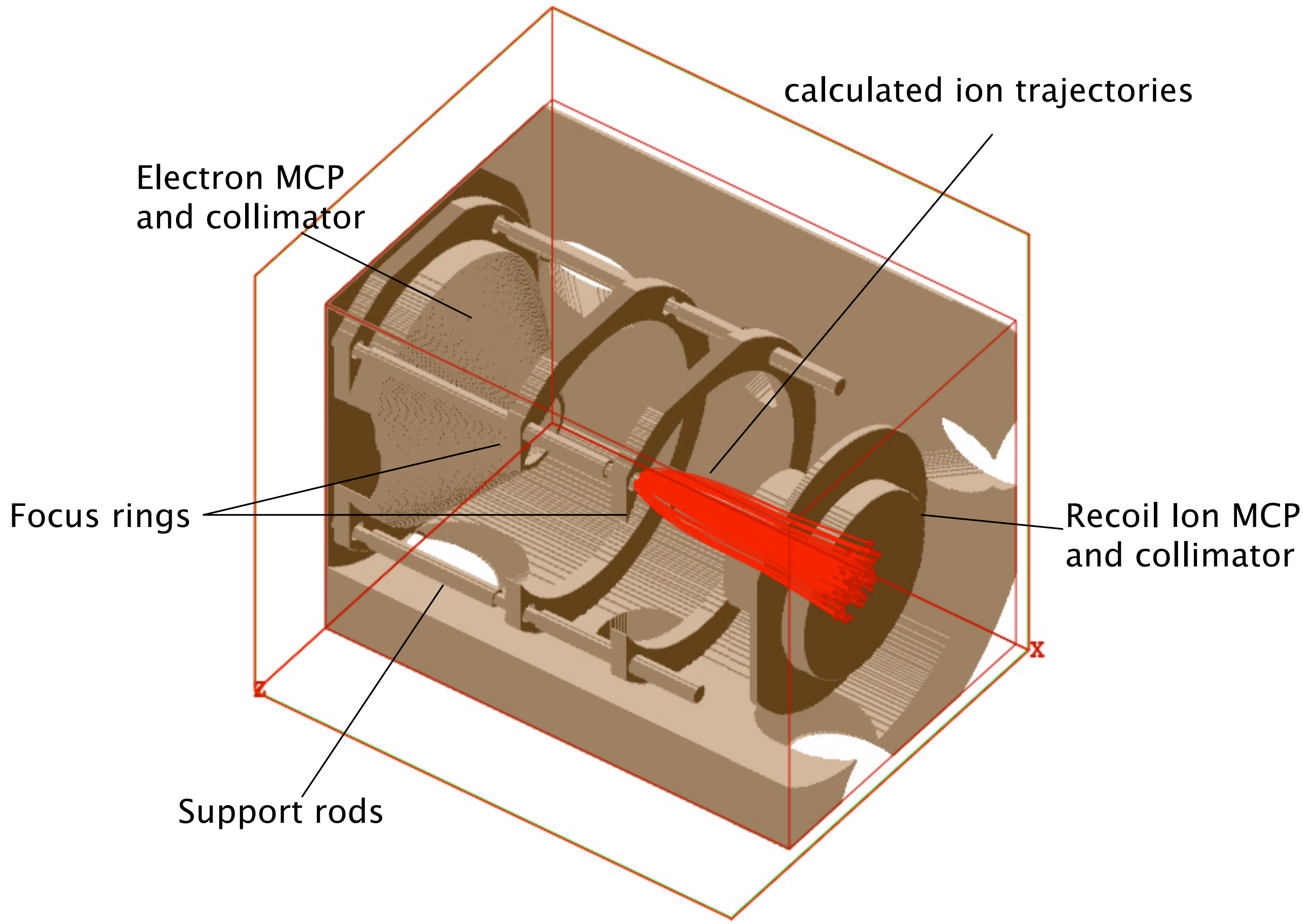


Apparatus schematic

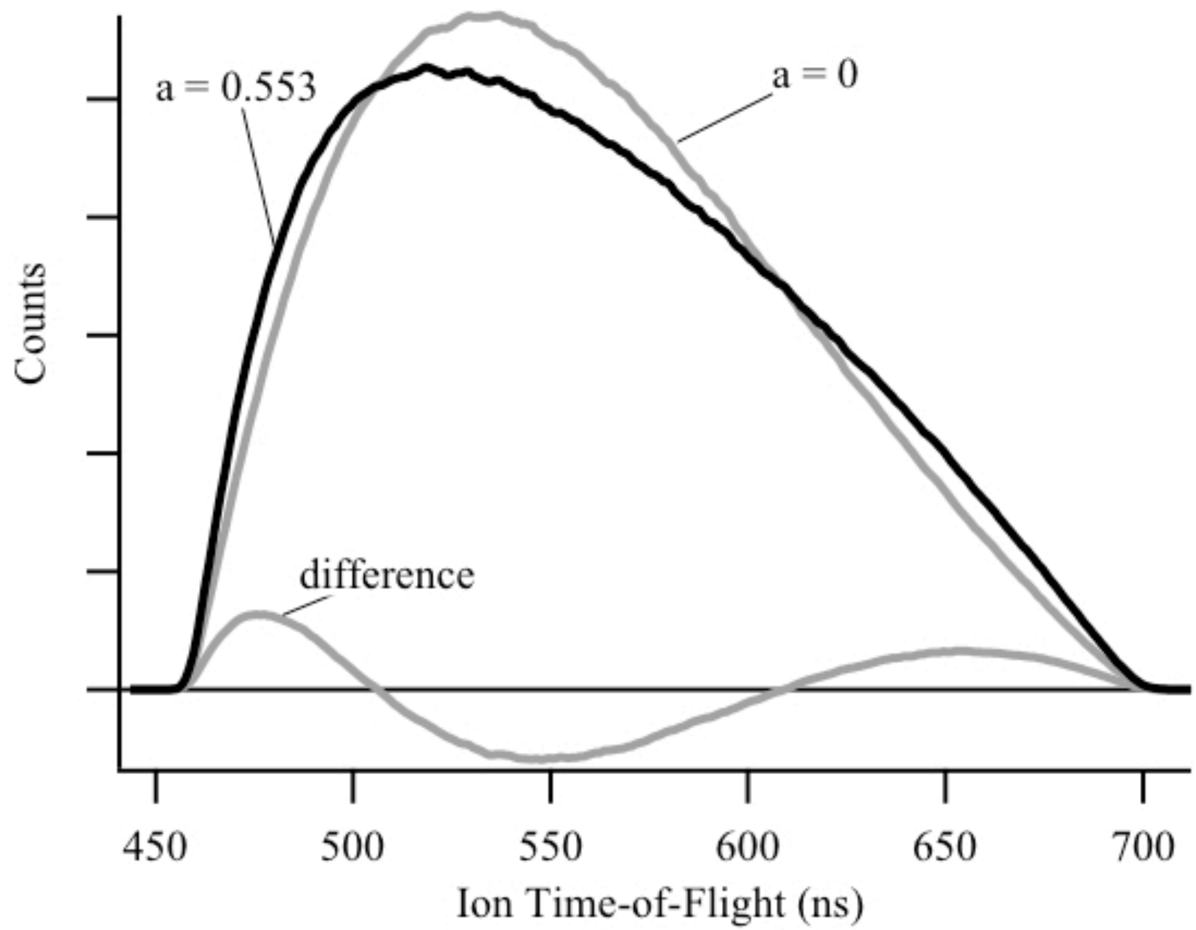


SimIon

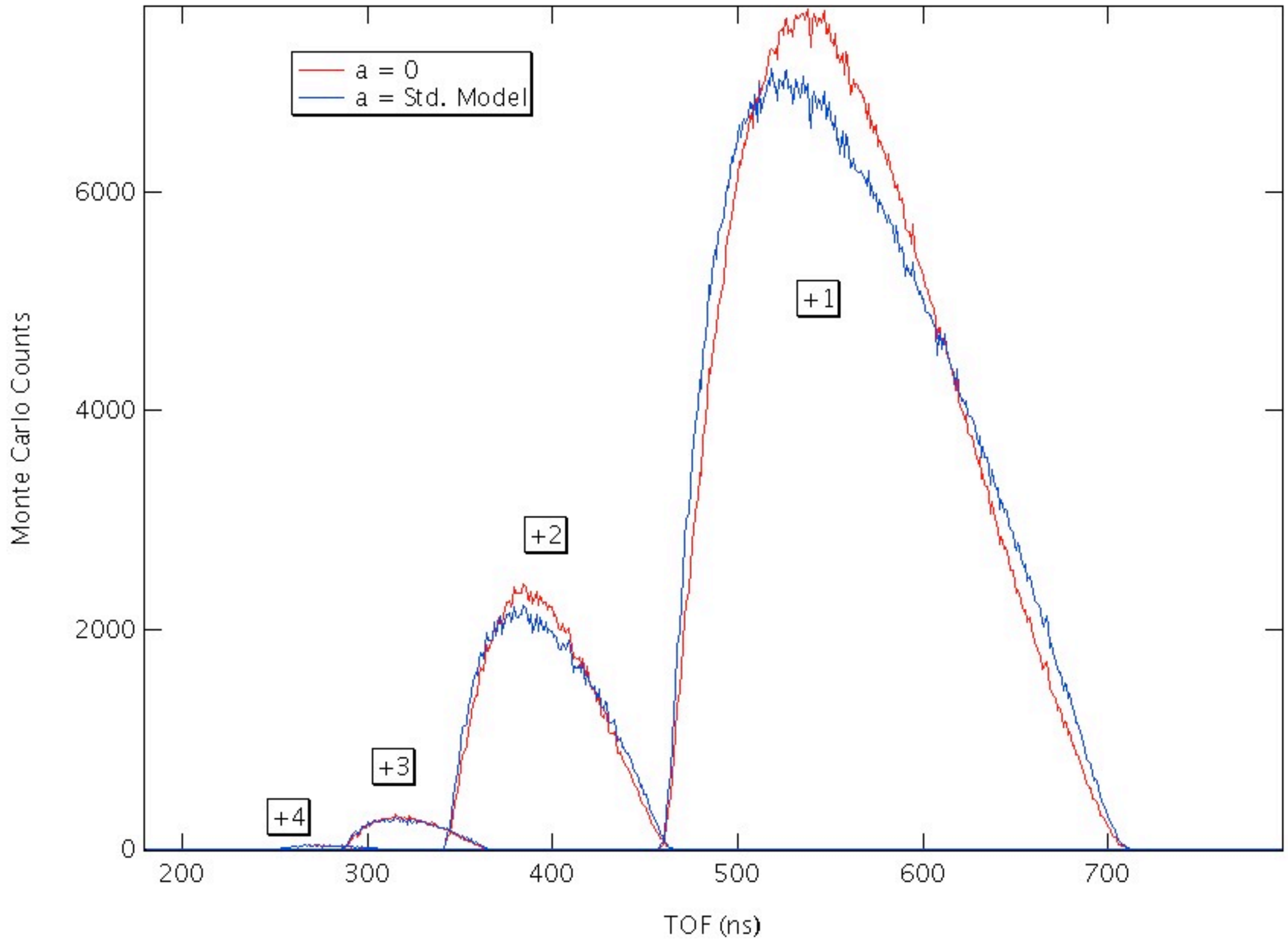
Cutaway view of the simulation volume inside the trapping vacuum chamber.



Calculated Time-of-Flight spectrum (Monte-Carlo)

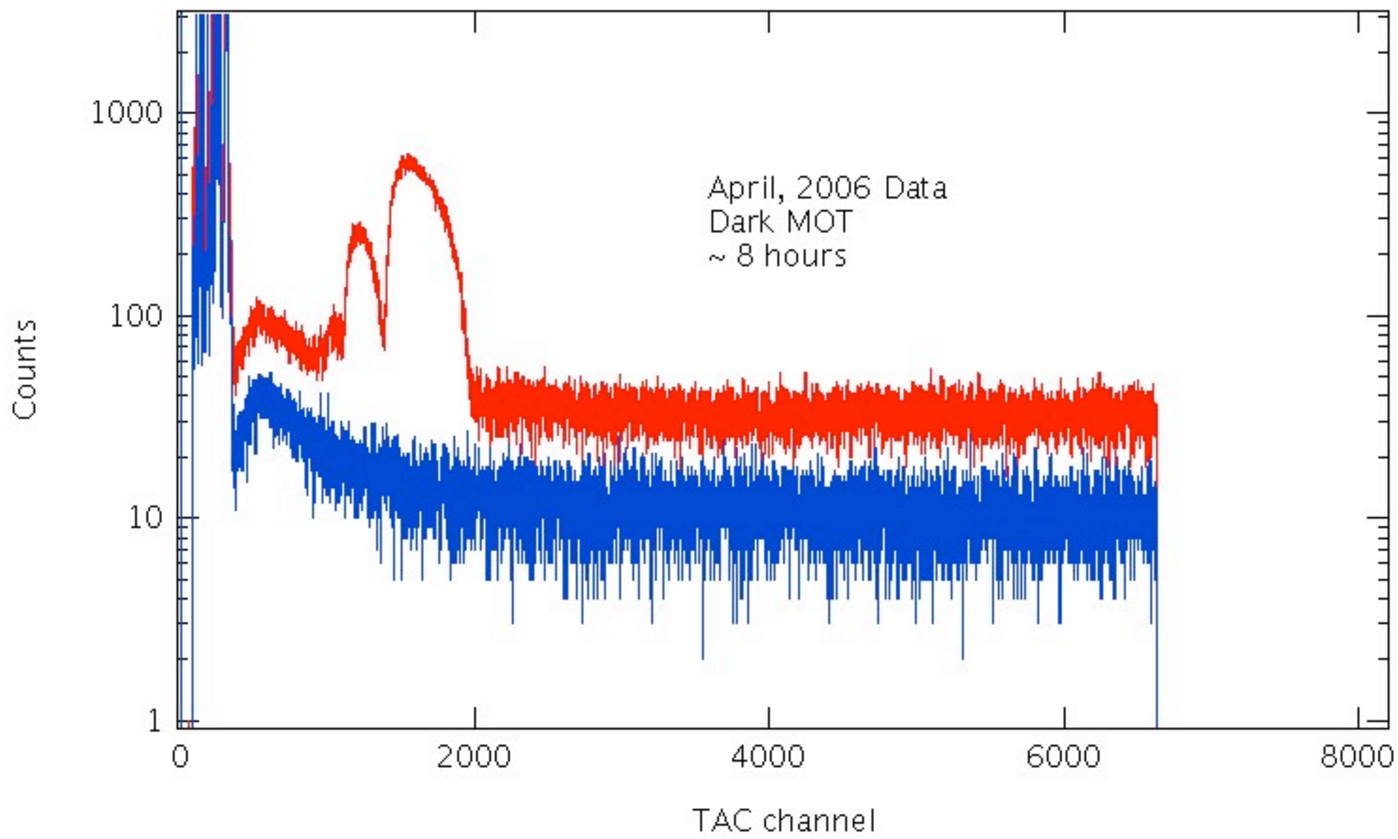


Several possible charge states of ^{21}Ne

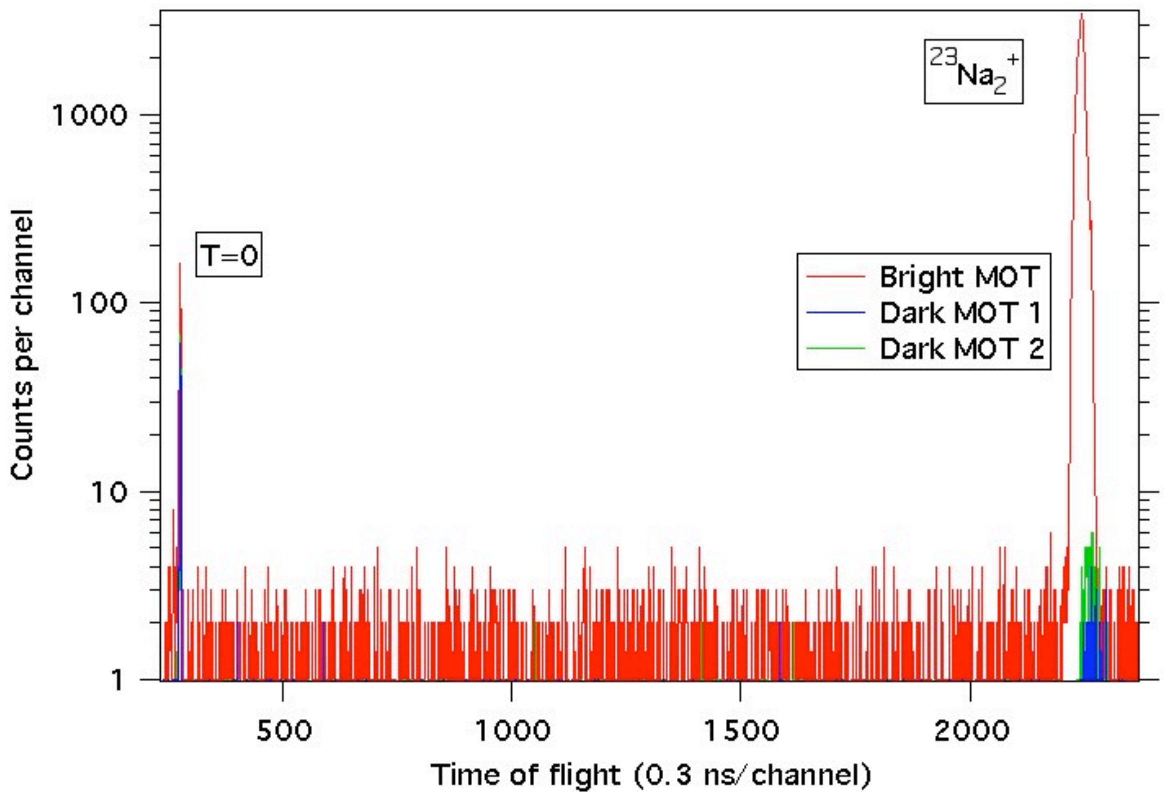


Time of Flight Data

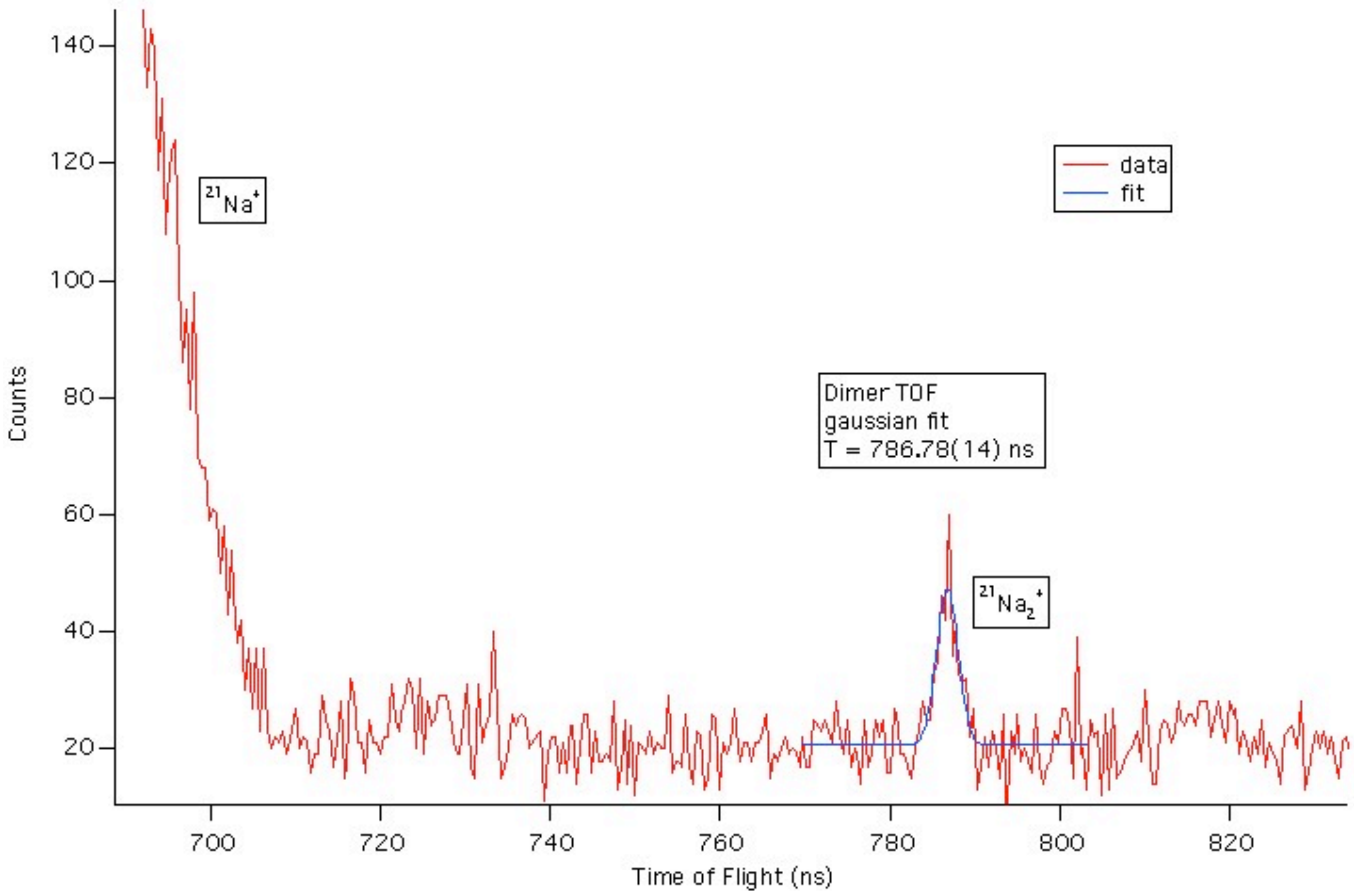
Representative Data



Surprise: Autoionized dimers of $^{23}Na_2^+$



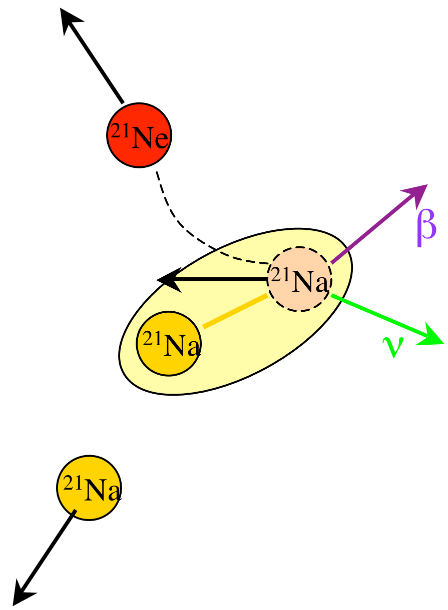
Radioactive Molecules



Beta decay in $^{21}Na_2$

$^{21}Na_2$ Formation rates in MOT are high

- Recoil ion scatters off interatomic potential at close range, changes momentum
- Initial momentum, energy distribution of ^{21}Ne is lost
- Depending on scattering parameters (b, θ) and $^{21}Ne^{+n}$ – ^{21}Na potential

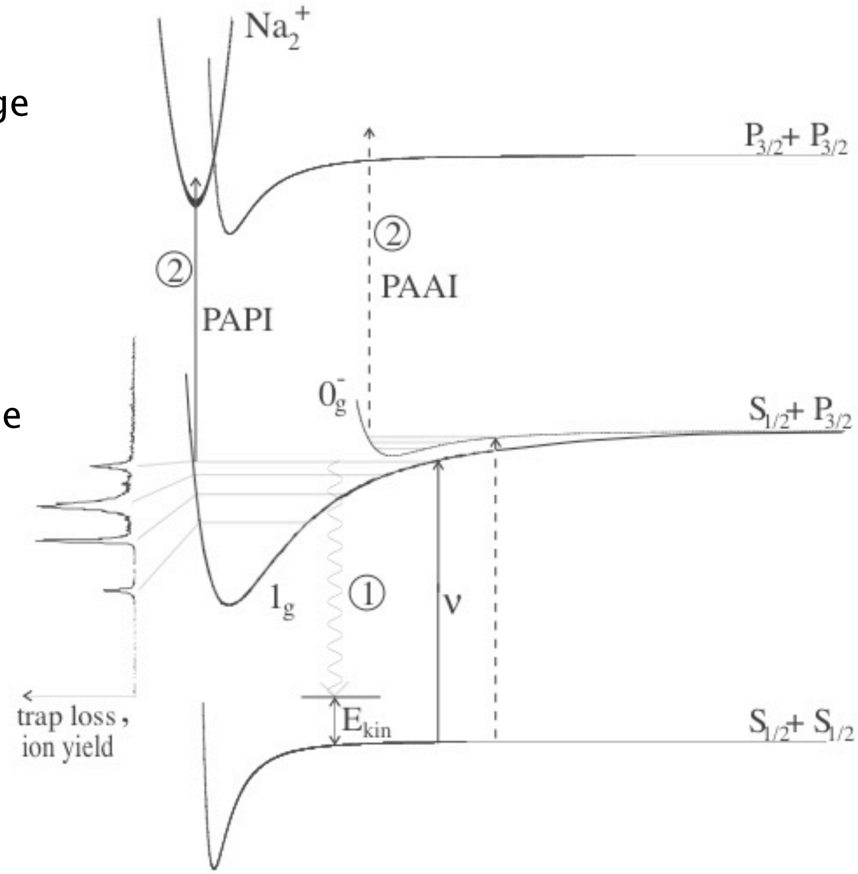


Photoassociation and Autoionization in Sodium

PAPI = Photoassociative Photoionization
Depends mostly on formation of short-range bound states

PAAI = Photoassociative Autoionization
Long-range bound states, not possible in single-color red-detuned experiment

PAPI dominates in Na_2, implying short-range excited states are populated.
These would be the most significant path to populate cold, bound, ground states



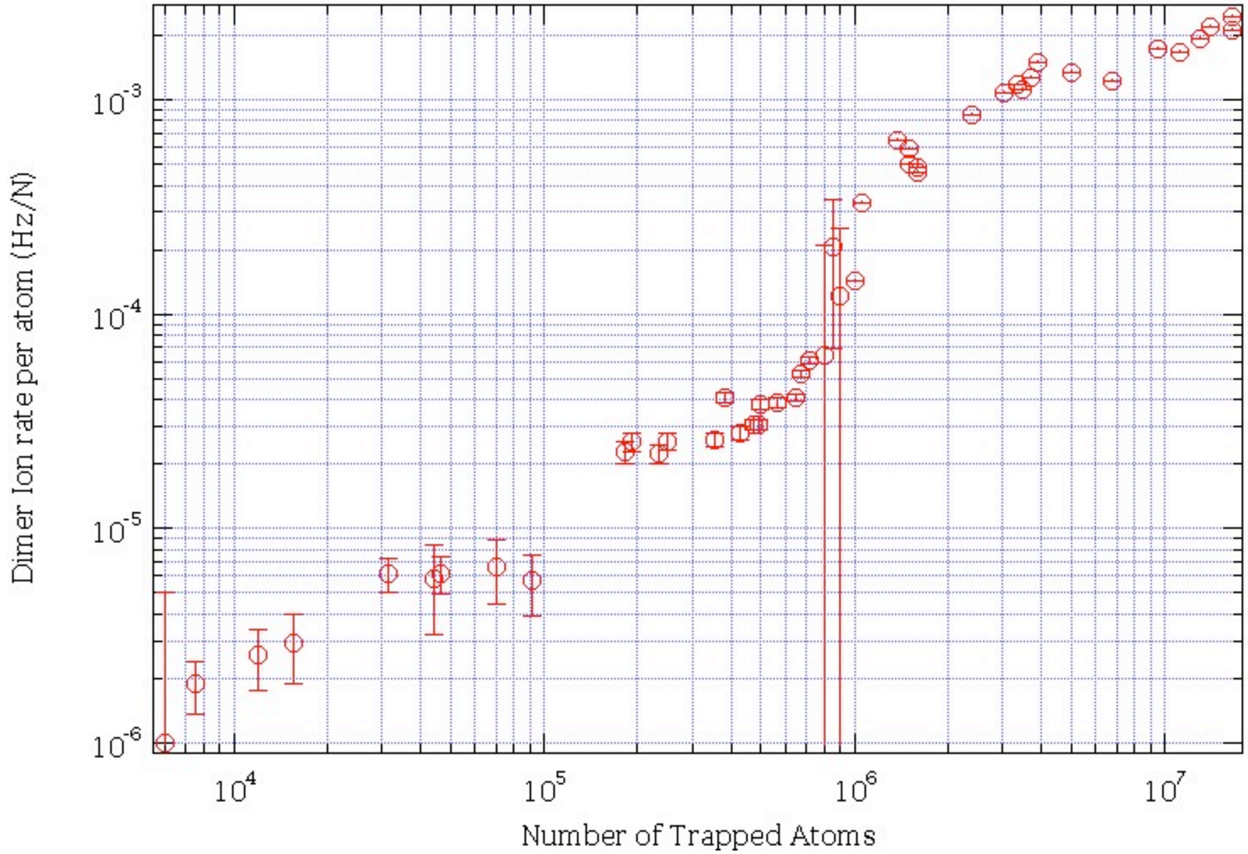
A. Amelink and P. van der Straten,Physica Scripta **68** C82 (2003)

Do small traps reduce the number of molecules?

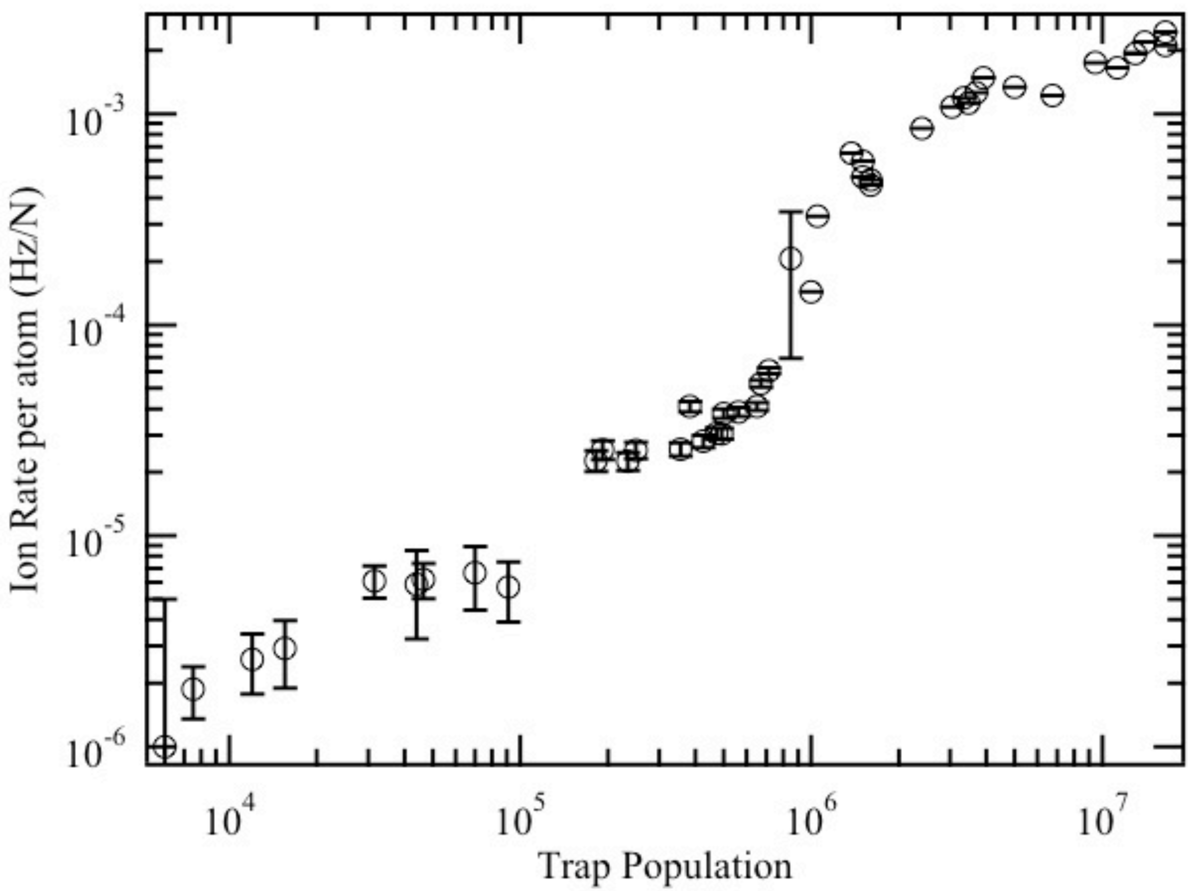
Number of ionized dimer $^{23}Na_2^+$ molecules detected with MCP's vs. atom trap population

Number of molecules relative to the trap population (N_{mol}/N_{atom})

Perturbation on $a_{\beta\nu}$ $\propto$ number of counts from molecular decays relative to counts from atomic decays



The number of dimers relative to the atomic population falls steeply at small trap sizes.



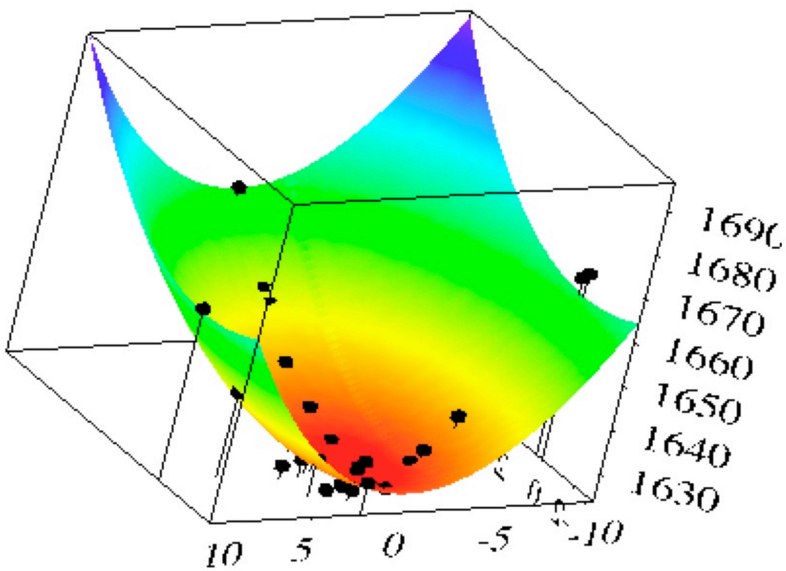
Ion Rate per atom (Hz/N)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{4}
10^{5}
10^{6}
10^{7}
Trap Population

Sometimes molecules are useful
Determining the Trap Position

Measure the stable dimer ions' TOF and positions on the MCP.

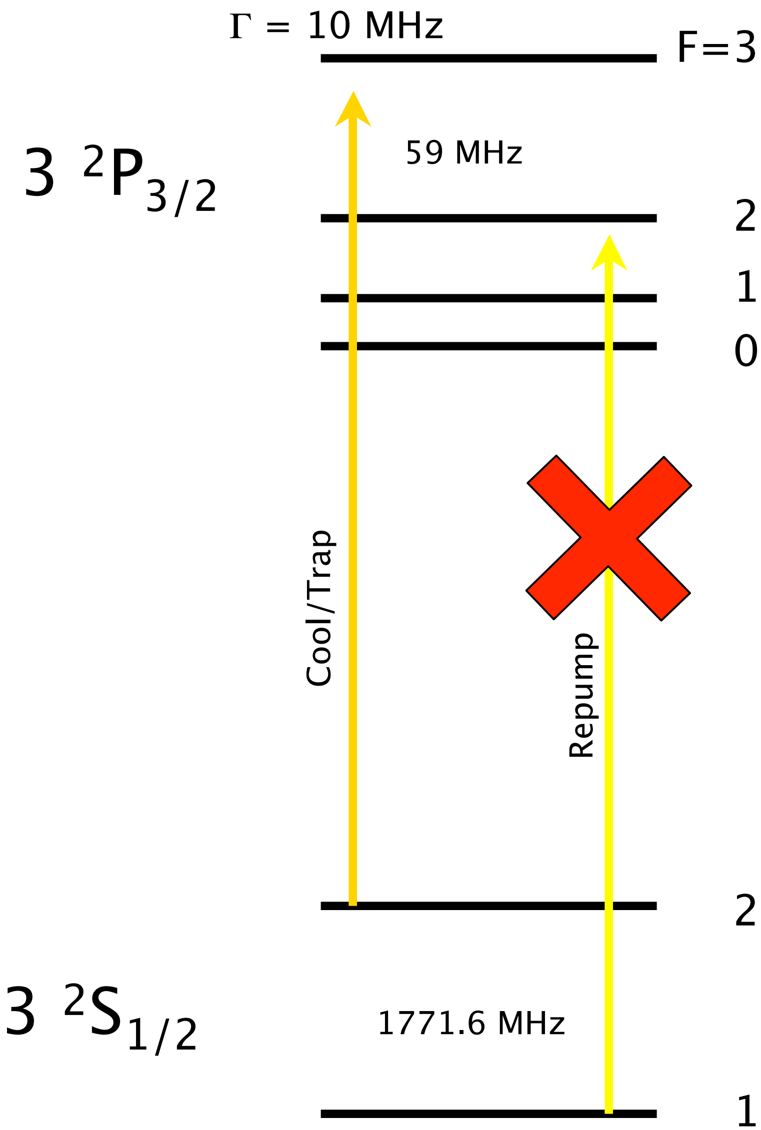
Move the MOT by dragging with magnetic field.

Find the location of the minimum time-of-flight of 23Na2+ in the horizontal and vertical axis by fitting TOF to a 2-D parabola:



Wire crossing point = (84.74, 86.21)
SimIon (Y,Z)

Reduce molecular formation rate with a Dark Trap



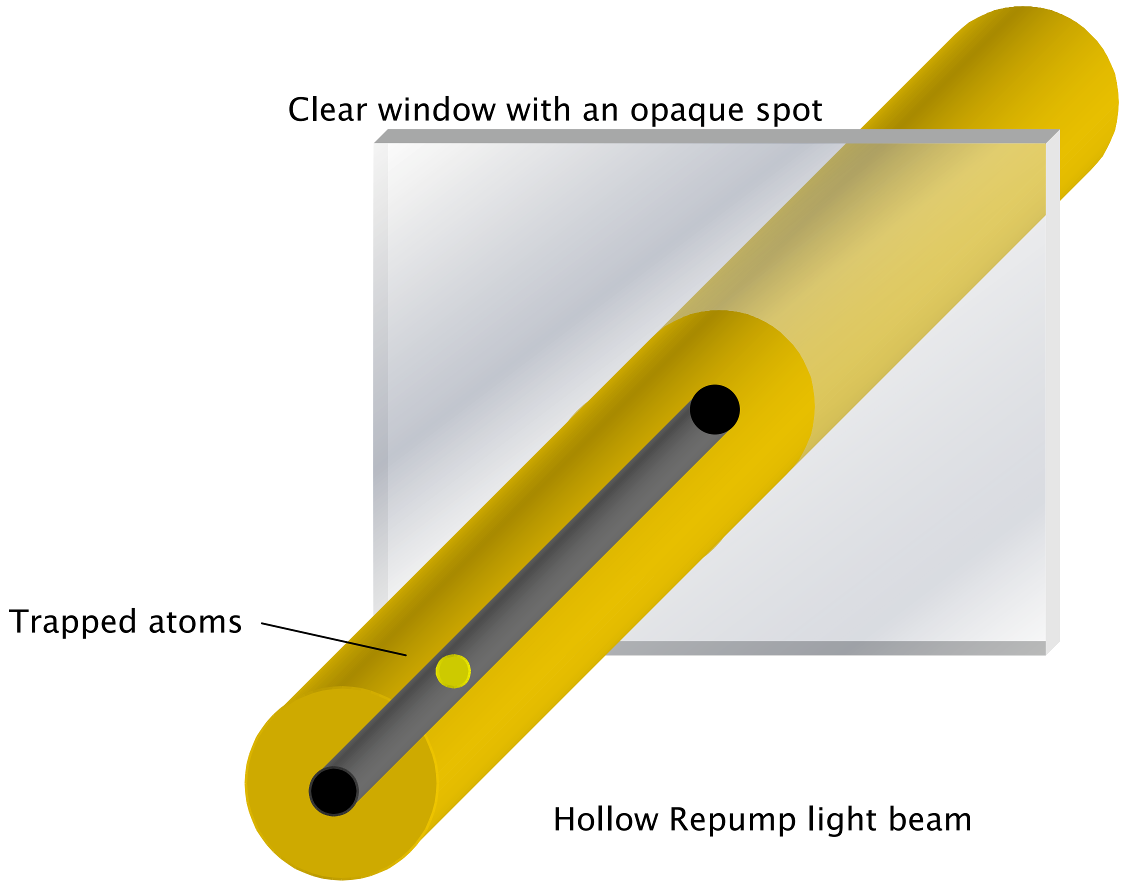
Turn off repump light on trapped atoms

Optically pump to $F_g = 1$

Atoms no longer see resonant light, Remain in 3 $^2S_{1/2}$

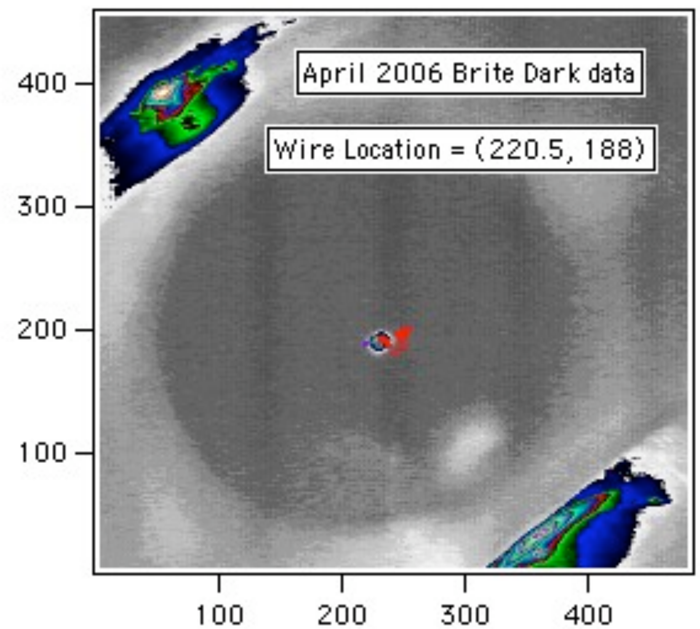
Collisions between ground state atoms Can't readily form bound molecules.

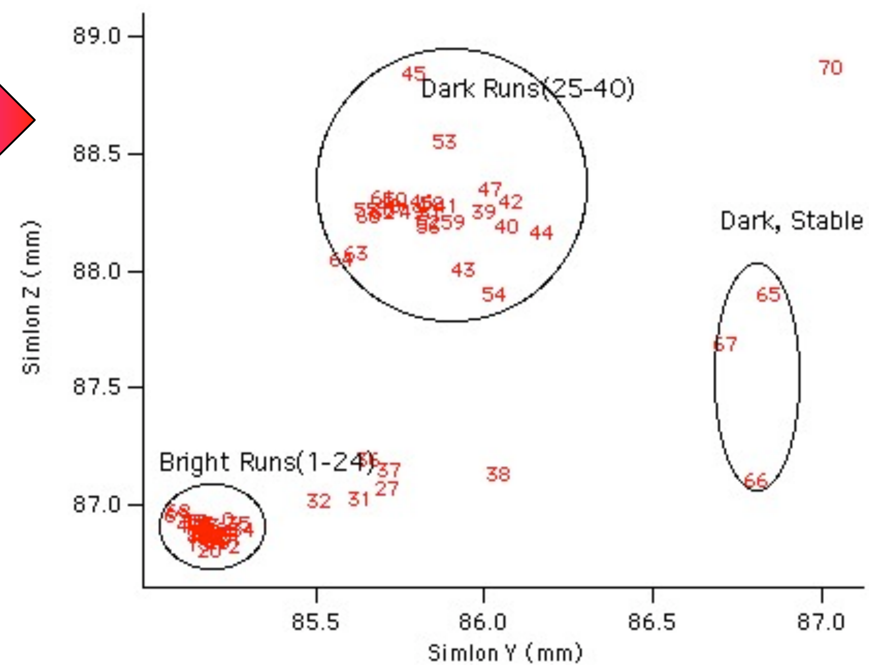
Dark MOT geometry



For each data run, determine the trap location

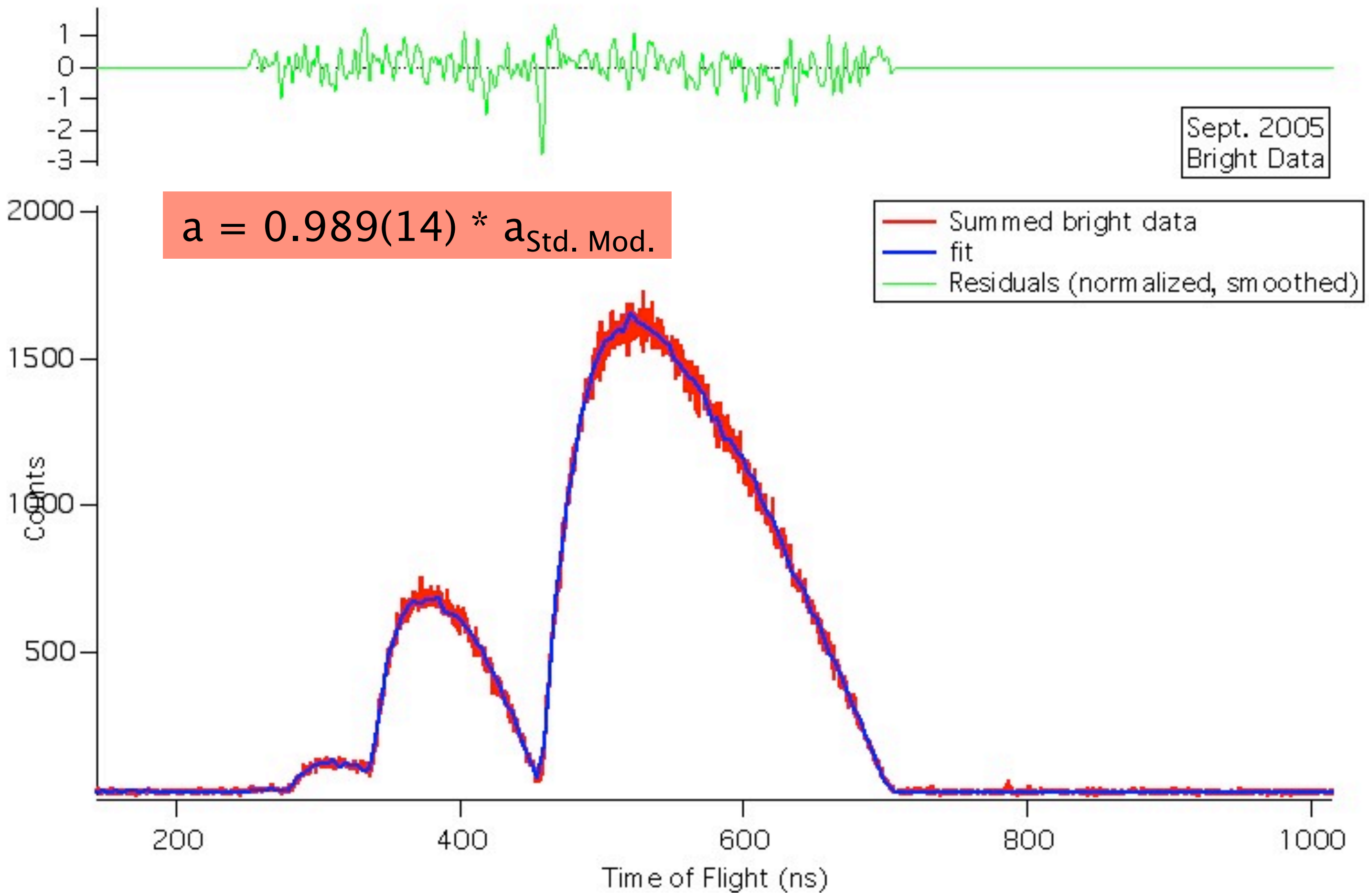
Red dots=location of various runs
combined on one representative image



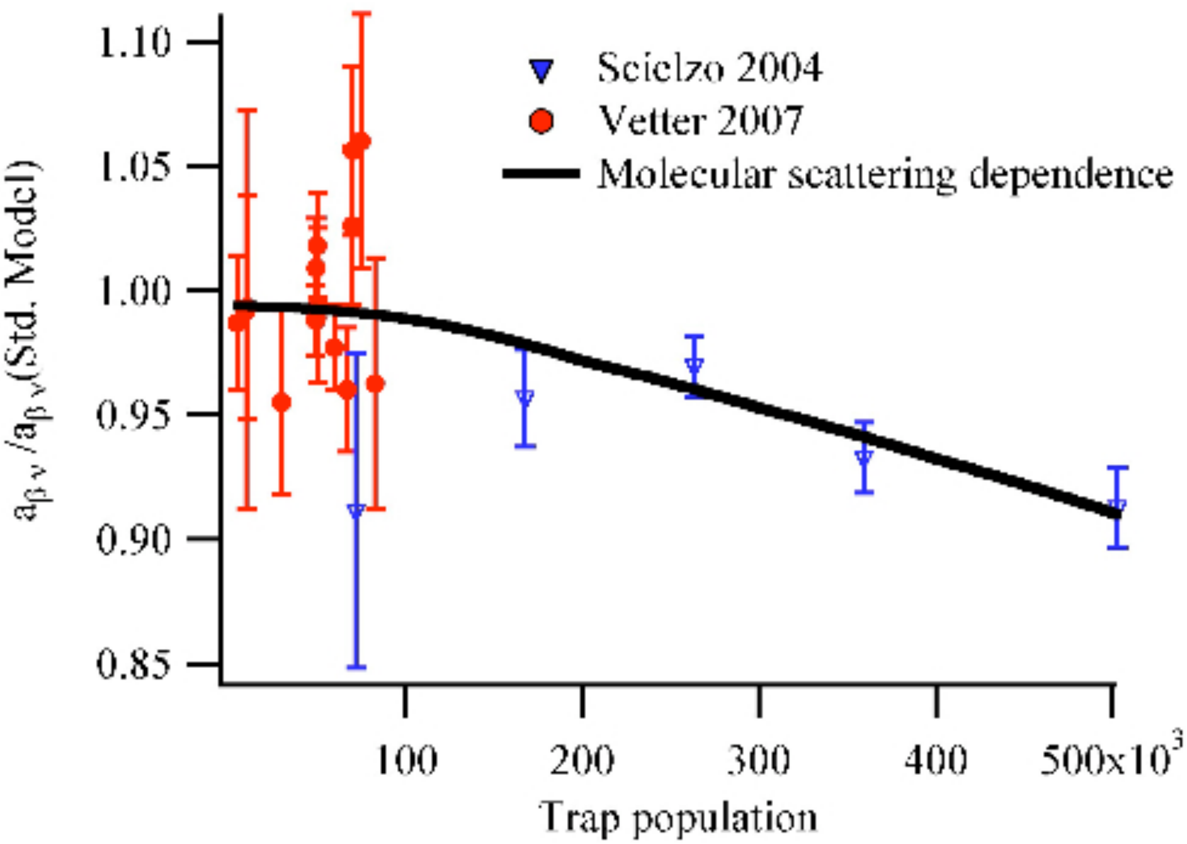


Feb. 25, 2008

Sample Data and Fit



Current and previous data



The answer

$a_{\beta\nu}$ = 0.9932 (69)(85) stat sys * a_{StdMod}

a_{StdMod} = 0.553(2) Hardy, 2006 + Mass, Q, B.R.

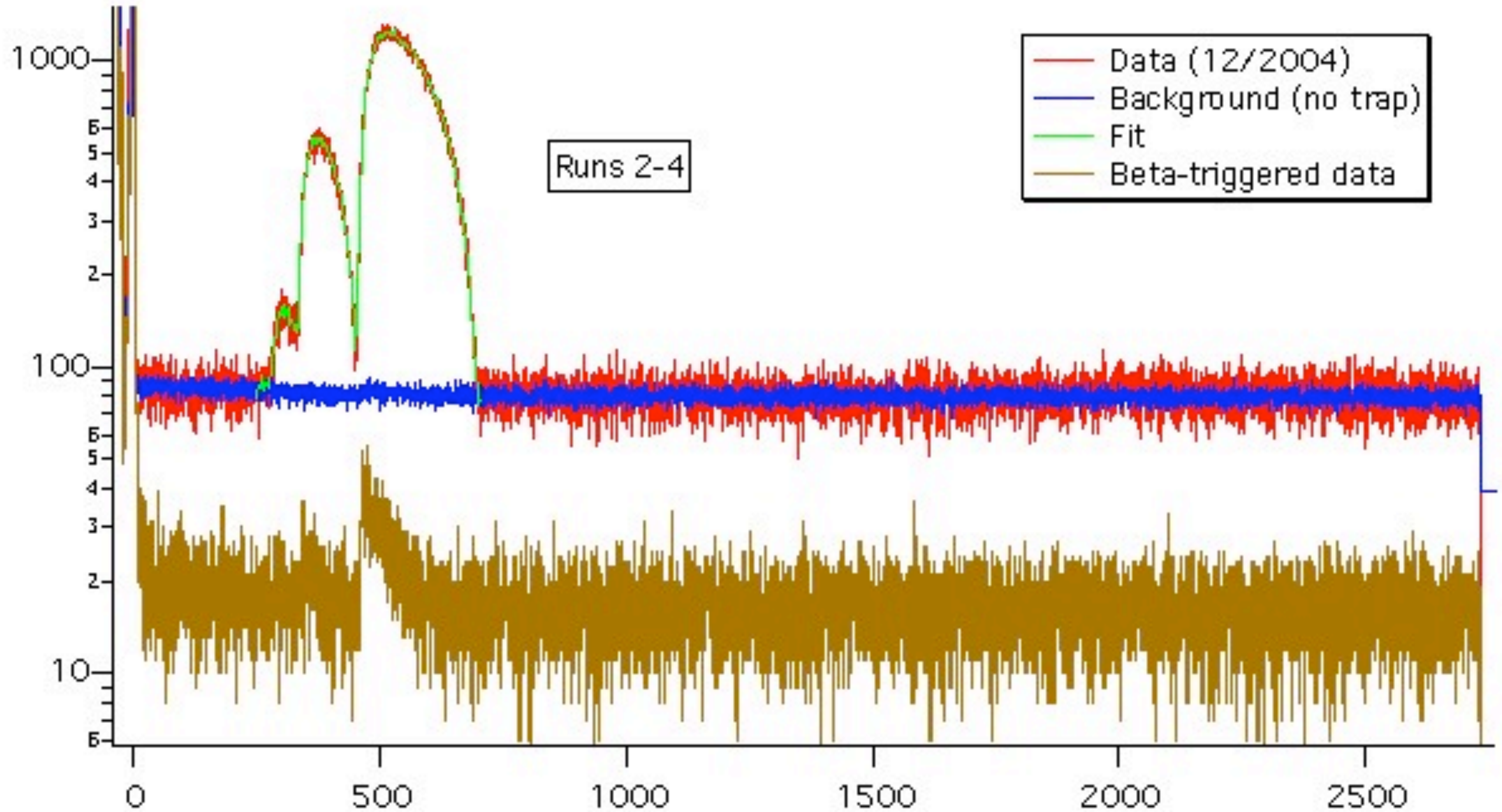
$a_{\beta\nu}$ = 0.5502 (38) (46) (20)
[stat] [sys] [model]

Systematic uncertainties

Most studied via Monte-Carlo comparisons:
generate "clean data" and "dirty data", then fit "dirty data" using "clean"

Source of Uncertainty	Correction to $a_{\beta\nu}$	Uncertainty in $a_{\beta\nu}$
Beta trigger electron MCP	Δa = – 0.5(4)%	0.4%
Recoil Ionization	Δa = – 0.4(2)% Nick had: Δa = – 0.6(3)%	0.2%
Polarization/Alignment	0	0.1%
MCP position dependent efficiency	Δa = + 0.25(15)%	0.15%
Simulation electrode position Electric field measurement uncertainty	0 0	0.25% 0.1%
MCP diameter uncertainty	Δa = –0.16(16)% (not applied)	0.17%
Trap size	$\Delta a/\Delta$(FWHM) = 0.044	0.5%
Trap position (X)	$\Delta a/\Delta x$ = 0.67%/mm	0.2%
Trap position (Y, Z)	$\Delta a/\Delta(z,y)$ = 1.5%/mm	+0.3% (one-sided)
Molecular scattering	Δa = –0.05%	0.05%
Internal conversion/excited state B.R.	Δa = +0.54%	0.13%
Total Uncertainty (Quadrature Sum)	**Δa = –0.11%**	**0.85%**
Physics (Ft value, branching ratio, recoil order)	$a_{\beta\nu}$ = 0.554(2)	0.36%

Beta-triggered event subtraction

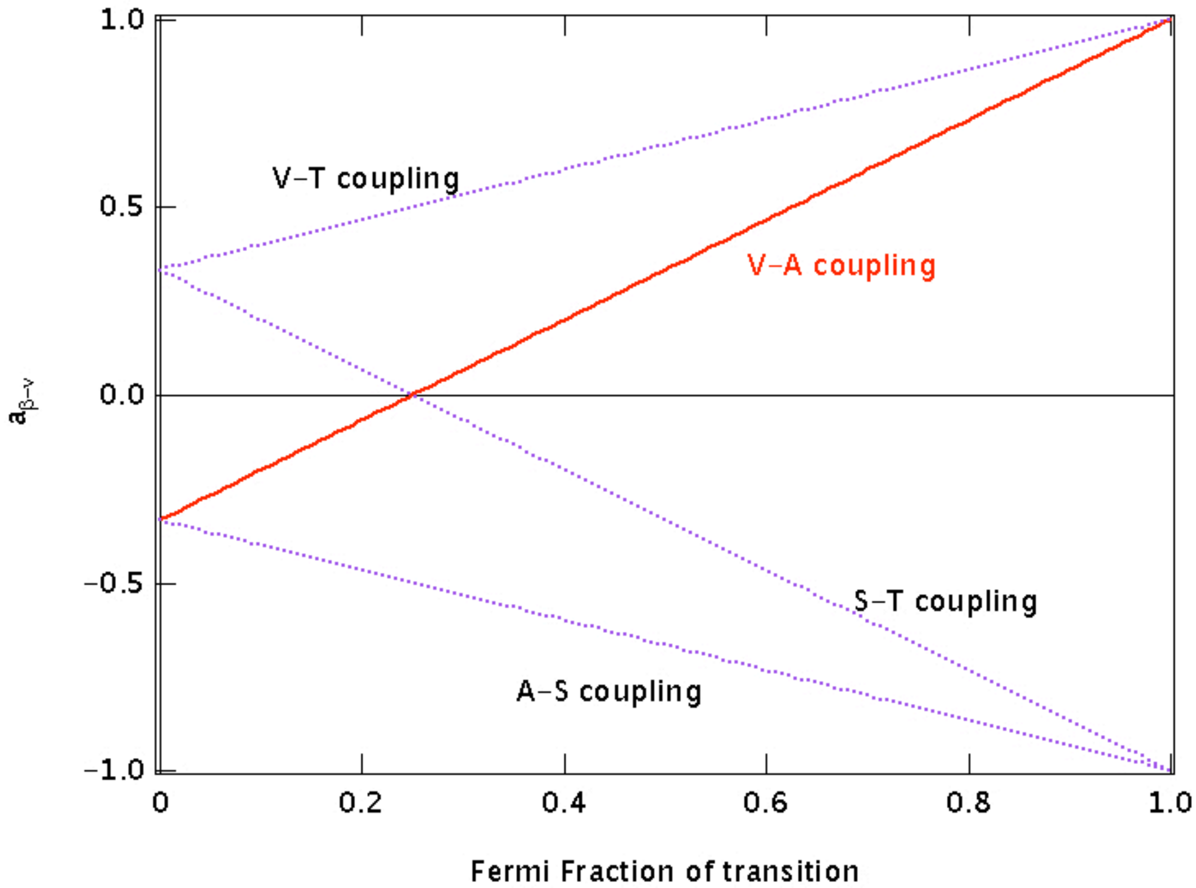


Data shows these events, with reduced efficiency. 3% relative detection efficiency
Unclear how to subtract from data -- need to know absolute detection efficiencies (multiple electron hits)

Not a large effect, however.

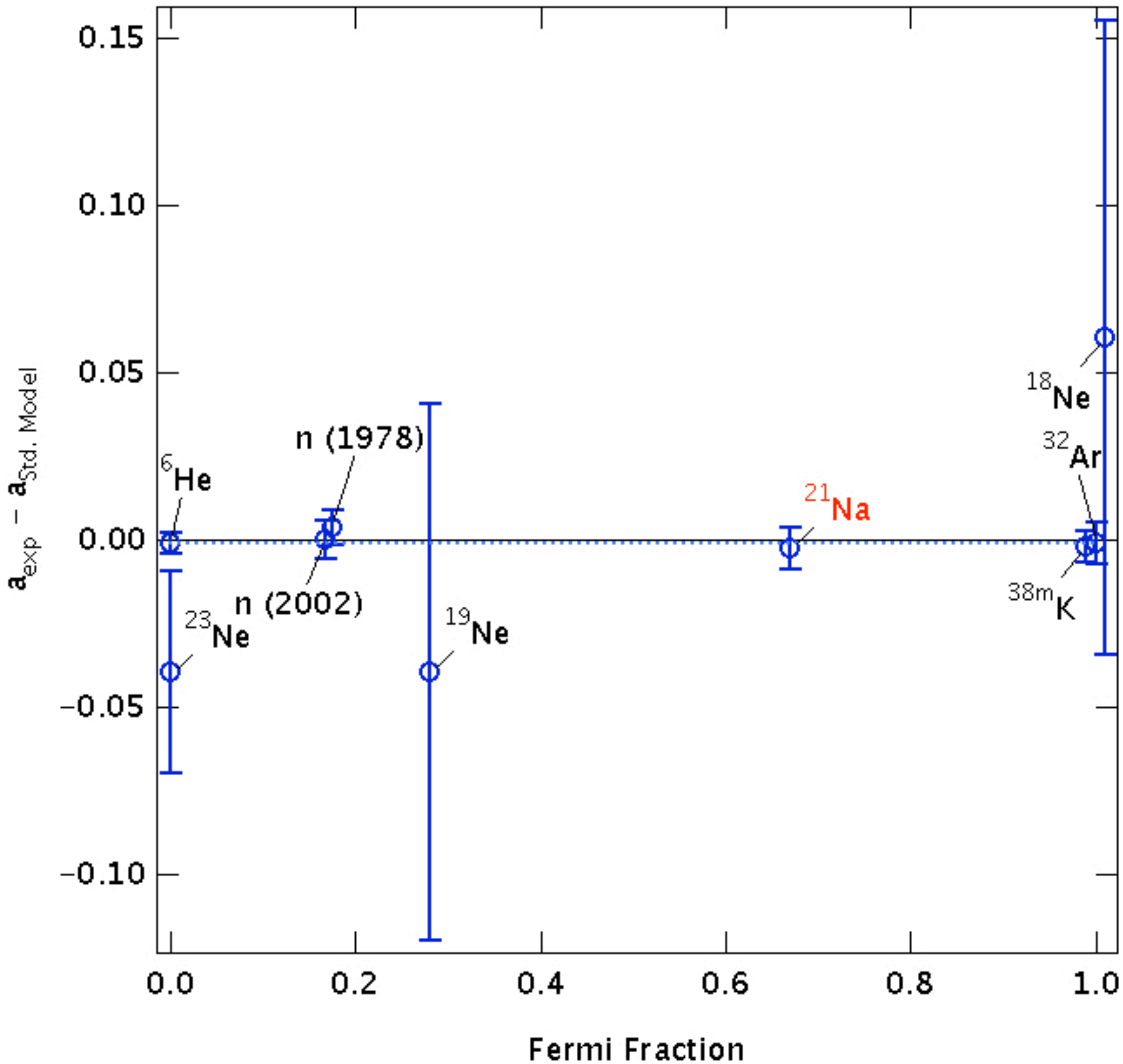
Beta Neutrino Correlation Measurements

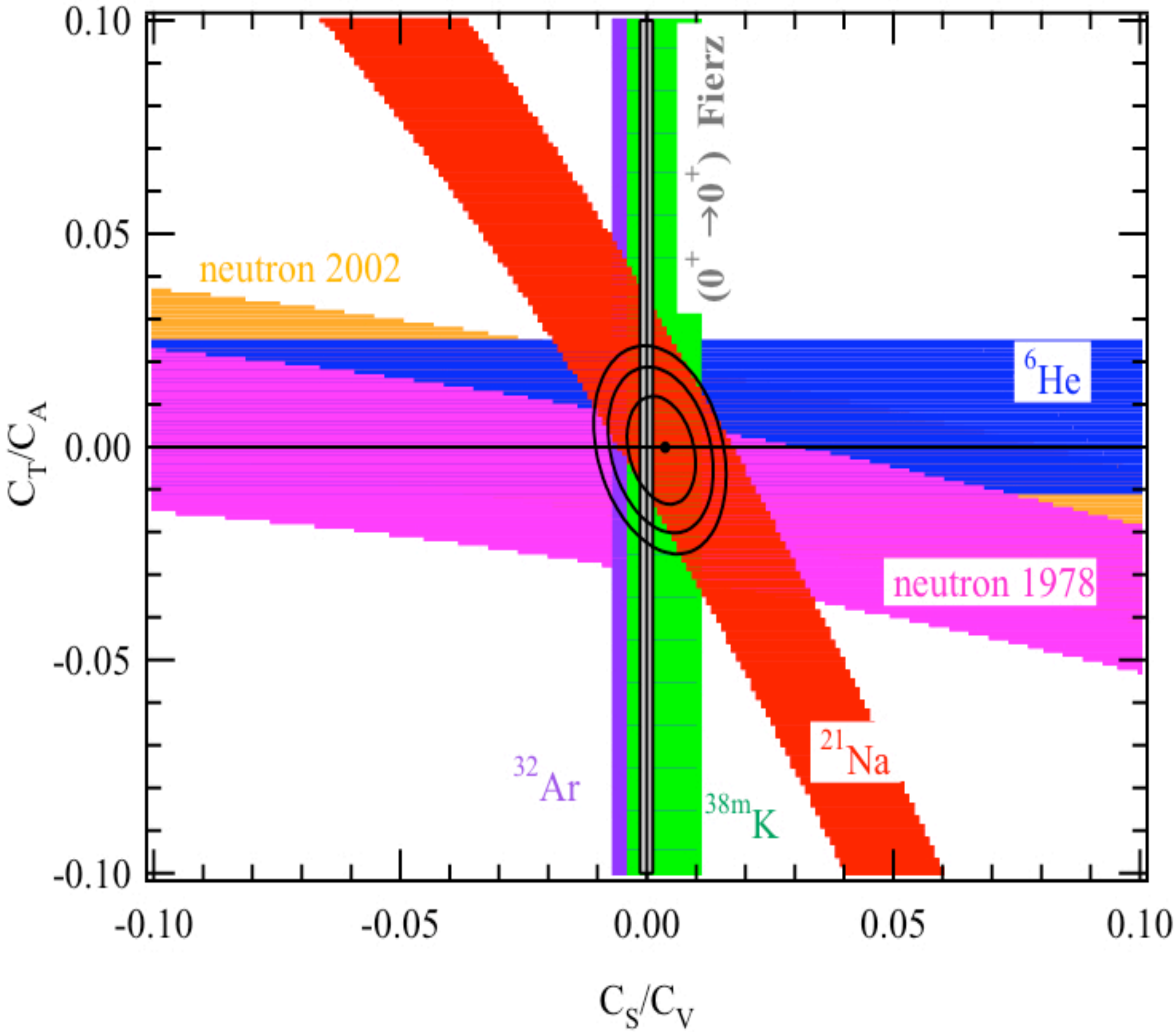
$a_{\beta\nu}$ plotted as a function of the Fermi fraction of the transition:



Beta Neutrino Correlation Measurements

Residuals to $a_{\beta\nu}$ as a function of the Fermi fraction of the transition:





0.10
0.05
0.00
-0.05
-0.10
-0.10
-0.05
0.00
0.05
0.10
C_T/C_A
C_S/C_V
neutron 2002
$(0^+ \rightarrow 0^+)$ Fierz
^{6}He
neutron 1978
^{21}Na
^{32}Ar
^{38m}K

Sensitivity depends on the Fierz term

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto 1 + a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + b_{\text{Fierz}}\frac{m_e}{E_e}$$

$$\tilde{a} = \frac{a_{\beta\nu}}{1 + b\frac{m_e}{\langle E_\beta \rangle}}$$

$$b\,\xi = \pm 2\sqrt{1-(Z\alpha)^2}\; Re\left[|M_F|^2 C_S C_V^* + |M_{GT}|^2 C_T C_A^*\right]$$

$$\frac{C_S}{C_V}, \frac{C_T}{C_A} < 0.01$$

Tests for new tree-level physics at 10 M_W or ~ 1 TeV

Implications for BSM physics

Several recent papers, very broad overview of experimental results and sensitivities to new physics

References:

S. Profumo, M.J. Ramsey-Musolf, and S. Tulin, "Supersymmetric Contributions to Weak Decay Correlation Coefficients," Phys. Rev. D **75**, 075017 (2007).

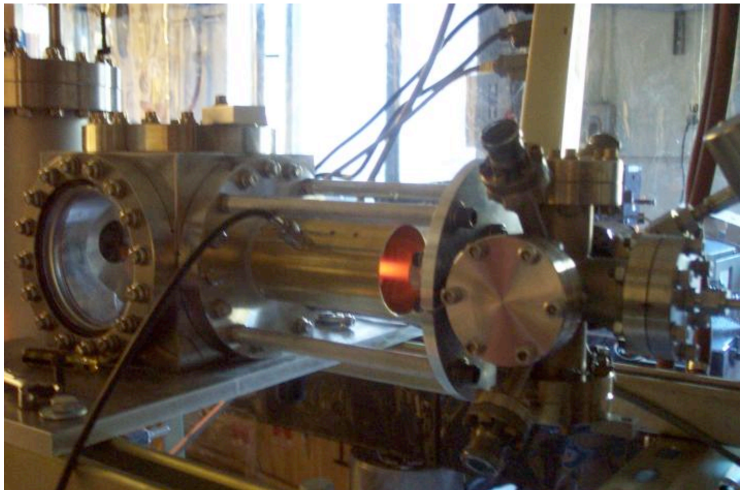
M.J. Ramsey-Musolf and S. Su, "Low Energy Precision Test of Supersymmetry," hep-ph/0612057.

N. Severijns, M. Beck, and O. Naviliat-Cuncic,
"Tests of the Electroweak Standard Model in nuclear beta decay,"
Rev. Mod. Phys. **78**, 991 (2006).

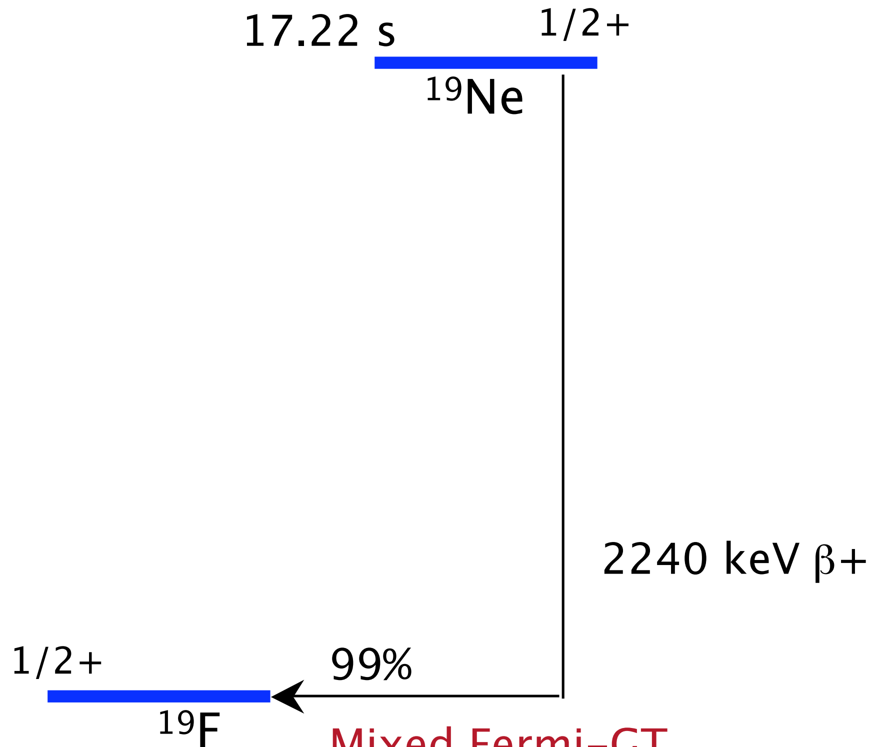
P. Herczeg, "Beta Decay Beyond the Standard Model," Prog. Part. Nucl. Phys. **46**, 413 (2001).

And others… (van Klinken, 1996)

Beta-neutrino correlation in Neon



Metastable neon atomic beam source



Mixed Fermi-GT

$\mathbf{a_{\beta\nu} \sim 0}$

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